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Was Archaeopteryx able to fly? Authentic palaeontological practices in a museum programme

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Resumen. La educación científica *auténtica* ha recibido una mayor atención en los últimos años, pero aún no está claro en qué consiste la autenticidad. Aquí, utilizamos conceptos de la Teoría Antropológica de lo Didáctico para acercarnos a la autenticidad. Tomamos como punto de partida un programa de educación de un museo y lo analizamos para determinar en qué constituye su autenticidad. A continuación, utilizamos la Teoría de Situaciones Didácticas para construir un modelo de referencia que constituye una versión optimizada con respecto a la autenticidad del programa. También se discuten brevemente las implicaciones de nuestros resultados.

Abstract. *Authentic* science education has received increased attention in recent years, but it remains unclear what constitutes authenticity. Here, we use notions from the Anthropological Theory of the Didactic to approach authenticity. We take a point of departure in an existing education programme in a museum, and analyse it to pinpoint what constitutes its authenticity. We then use the theory of didactical situations as a way to construct a reference model; this reference model constitutes an authenticity-optimised version of the programme. We conclude by briefly discussing the implications of our findings.

1. Introduction

Recent years have seen a strong interest in *authentic science* as a means to improve science education and ultimately, promote the formation of a scientifically literate citizenry. Authentic science education has been the subject of attention not only in education practice and research, but also at the policy level, both in the European Union (European Commission, 2007) and more recently, in the United States of America (National Research Council, 2012).

The adjective *authentic* is commonly used to describe something that “conform[s] to an original so as to reproduce essential features” (Merriam-Webster Online Dictionary, 2015). Authentic science education can thus be understood as science education that somehow reproduces essential features of science. However, authentic science education cannot succeed by simply reconstructing the external characteristics of the real scientist’s experience, because this in no way guarantees that learners will reconstruct the “inside” of that experience (Bain & Ellenbogen, 2002). Indeed, the frames of meaning that support and drive the work of scientists do not exist in educational contexts (Achiam, 2013; Fensham, 2001). On the other hand, the notion of authenticity does seem to denote some kind of proximity between the science of scientists and the science of learners. What, then, constitutes authenticity in a science education context?

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The present text attempts to answer this question with a point of departure in a museum programme for upper secondary school students, involving practical work with palaeontological specimens. Museums have a privileged relationship with a number of scientific disciplines because the practices and discourses of those disciplines have historically been closely intertwined with the collections of objects and specimens housed in the museum (Livingstone, 2003). This proximity means that with respect to expertise as well as access to objects and specimens, museums are well-positioned to offer potentially authentic object-based education programmes to support and complement school science. This case thus offers an opportunity to examine the notion of authenticity, and to reflect upon its more general implications for science education.

2. Theory

Authentic science education, just as any other type of science education, is the product of a process of didactic transposition (Chevallard, 1991) in which scientific knowledge, values and practices are selected from the scholarly domain and adapted to the domain of education (Clément, 2006). In this sense, science and nature museums are no different than other education settings such as schools, and indeed, the process of didactic (or *museographic*) transposition has been observed to occur in the development of science education environments in museums in many studies (e.g. Achiam & Marandino, 2014; Falcão et al., 2004; Marandino, 2004; Mortensen, 2010; Simonneaux & Jacobi, 1997). Accordingly, we use the framework of didactic transposition to map how science education is created through the progressive adaptation of scholarly palaeontology knowledge, values, and practices to a museum programme. In particular, we are interested in the emergence of the notion of “authenticity” in this process.

We then employ the framework of the epistemological reference model (Barbé, Bosch, Espinoza, & Gascón, 2005; Chevallard & Bosch, 2013) as a way to clarify our analytical proposal. We use the theory of didactical situations or TDS (Brousseau, 1997/2002) to construct this reference model, based on the empirical data of the four contexts involved in the didactic transposition. In the words of Brousseau, “the intellectual work of the student must at times be similar to [...] scientific activity” (1997/2002, p. 22). TDS specifies the conditions for the reproduction of bodies of knowledge that were originally produced in scholarly contexts (Bosch & Gascón, 2006), and is therefore well suited to generate reference models for authentic teaching-learning sequences, i.e., teaching-learning sequences that have optimal proximity to real science. The reference model thus represents what the organisation of palaeontological knowledge *could* be, including what the notion of authenticity *could* entail, in an educational setting (Chevallard & Bosch, 2013). We consider the reference model to be the main result of this study.

3. Contexts involved in the didactic transposition

The present text focuses on the palaeontology programme *Evolution: From Dinosaur to Bird*, a teaching sequence for upper secondary school students visiting the Natural History Museum of Denmark. In this programme, participants compare a modern bird skeleton to a fossil *Archaeopteryx* (see figure 1) to answer the question “was *Archaeopteryx* able to fly?”. In the following sections, we describe each of the contexts involved in the didactic transposition.

3.1. Scholarly context

Palaeontology is a scientific discipline that studies prehistoric life. It is a sub discipline of biology, and has substantial overlap with evolutionary biology. It is a historical science, meaning that it gathers evidence by observation because direct experimentation is often impossible (Gray, 2014). Fossils are the main sources of information in palaeontology, and they

differ from each other due to their unique fossilisation histories. This affects what can reliably be predicted from them (Ault & Dodick, 2010), because the particular features of any chosen specimen will affect the range of observations that are possible (Ostrom, 1979).

In the case of *Evolution: From Dinosaur to Bird*, the palaeontological evidence in question is the fossil of the animal *Archaeopteryx* (figure 1). The significance of *Archaeopteryx* is that it was the first fossil to be found that indicated the evolutionary origins of birds by having a “reptilian” skeleton, but also unmistakably wearing feathers (Ostrom, 1975). As feathers had hitherto been considered a key character of birds (Wellnhofer, 2004), and an adaptation for flight (Padian & Chiappe, 1998), the discovery of the feathered *Archaeopteryx* raised the question of whether it had been capable of active, flapping flight. To this date, eleven fossilised *Archaeopteryx* specimens have been discovered.

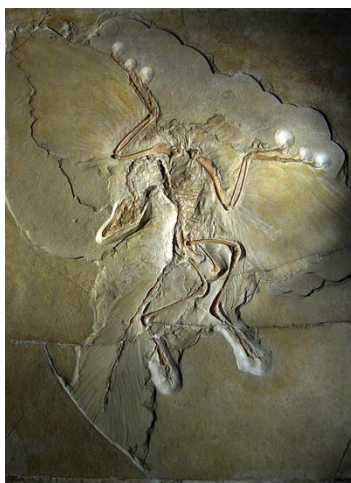


Figure 1. The fossil *Archaeopteryx* (the Berlin specimen), photographed at Museum für Naturkunde in Berlin. Image courtesy of H. Raab, licensed through Creative Commons. Link to material: [https://commons.wikimedia.org/wiki/File:Archaeopteryx_lithographica_\(Berlin_specimen\).jpg](https://commons.wikimedia.org/wiki/File:Archaeopteryx_lithographica_(Berlin_specimen).jpg). No alterations have been made.

To answer the question of whether *Archaeopteryx* had been able to fly, palaeontologists utilise a practice of inquiry known as comparative anatomy (von Bonin, 1946) in which shared anatomical features of extinct organisms are compared to those of organisms with known capabilities. These comparisons include both homologies (characteristics in different organisms that are similar because they were inherited from a common ancestor, e.g. feathers in *Archaeopteryx* and modern birds) and analogies (characteristics in different organisms that have separate evolutionary origins, but are superficially similar due to similar selection pressures, e.g. wings in bats and birds).

The anatomies of various known fliers, e.g. pterosaurs, bats and birds, have been compared to that of *Archaeopteryx* in a number of ways, including morphological comparisons, bone density comparisons, and energy consumption calculations (Feduccia, 1993; Gatesy & Dial, 1996; Gatesy & Middleton, 2007; Norberg, 1995). In the following, we have selected two palaeontological trajectories of inquiry to illustrate how scholars work to produce knowledge through comparative anatomy practices.

Example: The furcula. The avian furcula (figure 2A) is thought to be formed from a fusion of the clavicles. It is generally interpreted as an adaptation of the bird flight apparatus (Ostrom, 1979), where its role may vary from that of a strut or a brace to stabilise the pectoral girdle to that of a spring to enhance wing movement (Bock, 2013; Goslow, Dial, & Jenkins, 1990). Of the eleven *Archaeopteryx* specimens that have been discovered, only the London, Thermopolis and Maxberg specimens include the boomerang-shaped structure believed to be a strut-like furcula. The

presence of the furcula in these three specimens has been interpreted to mean that *Archaeopteryx* was capable of flight (Olson & Feduccia, 1979; Ostrom, 1979; Padian & Chiappe, 1998), while its absence in the other known specimens has been explained by incomplete fossilisation. This trajectory of inquiry is summed up in the scholarly praxeology shown in figure 2B.

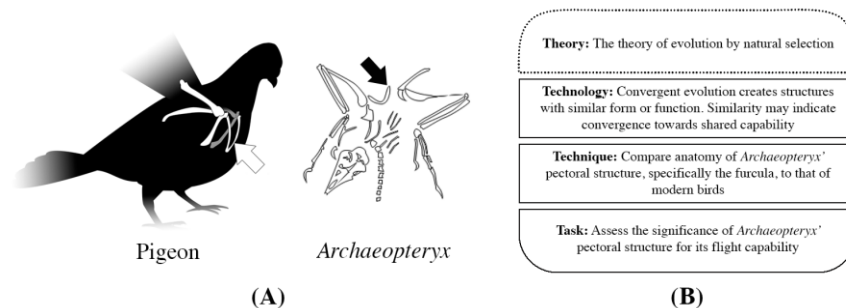


Figure 2. The observation of the furcula on a modern bird and its comparison to that of *Archaeopteryx* (here, the Thermopolis specimen) (A) can be expressed in the scholarly praxeology (B). It describes the task, the technique, the technology justifying the claim that *Archaeopteryx* could have been a flier, and the overarching theory that (implicitly) justifies the technology. Pigeon redrawn from Kershaw (1988).

Example: The tail. A striking feature of *Archaeopteryx* is its long, flexible tail, which consists of a large number of vertebrae (figure 3A). This long tail would have handicapped it somewhat during flight by increasing drag (Norberg, 1995), but also because the mechanical linkages between the individual vertebrae probably hampered coordinated turning (Gatesy & Dial, 1996). In comparison, a modern bird has a short, stiff tail with a reduced number of fused caudal vertebrae (pygostyle; figure 3A). This is advantageous in flight because it reduces drag and energy expenditure, but also because it reduces the part of the modern bird's body weight that is far from its centre of gravity (Zhou & Li, 2010). Accordingly, *Archaeopteryx*' long tail is interpreted as a contraindication of its flight capability (figure 3B).

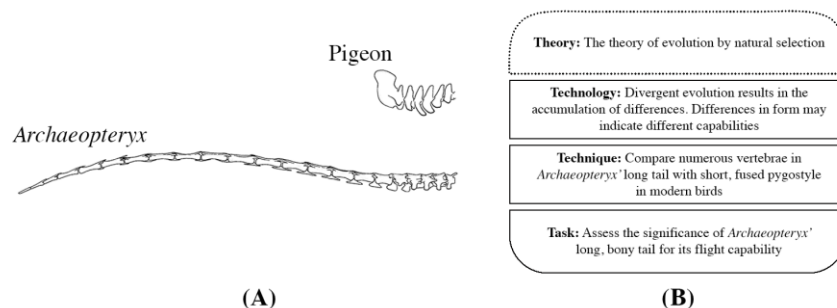


Figure 3. The comparison of *Archaeopteryx*' long bony tail to the pygostyle of a modern bird (A) and its interpretation, expressed as a scholarly praxeology (B). *Archaeopteryx* tail and bird pygostyle redrawn from Gatesy and Dial (1996).

3.2. Noosphere context

For natural history museums, fossils are non-renewable natural resources that relate to the evolutionary history of living things (Ladkin et al., 2010). Fossils form an important part of natural history museums' collections for the historical and descriptive sciences, i.e. palaeontology, evolutionary biology, or geology (Livingstone, 2003). In particular, the collections of the Natural History Museum of Denmark are seen as an important tool for the Museum's own research but also for the research of other institutions (Natural History Museum of Denmark, 2013a). In addition, these collections are seen to have an educational purpose, as described by the Museum's Head of Education:

The educational programming of the Natural History Museum of Denmark takes a point of departure in the scientific method and in the practical work of the participants, who interact with authentic materials that could potentially come from the Museum's collections (Head of Education K. E. Vad, personal communication, 22/10/13).

The Head of Education further emphasises that it is not sufficient for participants in the Museum's programmes to have their hands on the materials and objects; they must "use them as evidence and tools in their own investigations and observations" (K. E. Vad, personal communication, 22/10/13).

Another important actor in the noosphere is the Ministry of Education, because it legislates about the curriculum of the upper secondary school students who are the intended audience of the Natural History Museum's educational programming. The sub discipline of palaeontology is not mentioned in the upper secondary school curriculum guidelines; however, the Danish Ministry of Education describes upper secondary school biology in the following way:

"a scientific subject with an emphasis on experimental methods in the laboratory as well as in nature. [...] The taught subject takes a point of departure in the scientific discipline. [...] Students should be able to explain and apply biological theory and method, including [...] the analysis and interpretation of data from experimental work" (Ministry of Education, 2010).

The curriculum guidelines further state that biology students should work with the scientific method "with an increasing degree of autonomy" throughout their course of study (Ministry of Education, 2010). Scientific objects and specimens are not mentioned explicitly as sources of knowledge.

3.3. Educator context

The programme *Evolution: From Dinosaur to Bird* is a 90-minute teaching sequence for upper secondary school students visiting the Natural History Museum of Denmark. The programme has been developed by one of the Museum's Educators (the second author), who has a Ph.D. in palaeontology. The Museum's web site describes the programme in the following way:

How did birds evolve, and what did they evolve from? What information is available in a 145 million year old fossil? The evolution of birds is exemplary for our understanding of the concept of evolution. In this programme, the students examine and compare fossils of the dinosaur-bird *Archaeopteryx* with skeletons of modern birds. Observations of similarities and differences form the basis of a discussion of the evolutionary development from dinosaurs to birds. The programme begins and ends with a visit to the Museum's exhibitions (Natural History Museum of Denmark, 2013b, authors' translation).

In particular, we have focused our attention on a 40-minute exercise where participants compare a modern bird skeleton to the fossil *Archaeopteryx*. In this exercise, the Museum Educator provides the participants with the research question (was *Archaeopteryx* able to fly?), and then withdraws to allow the participants to determine the method of investigation and interpretation.

The objects chosen for this exercise are a replica of *Archaeopteryx* (the Berlin specimen) and a bird skeleton, prepared by the Museum's taxidermists. The bird skeletons used in the exercise include a Carrion Crow (*Corvus corone*), a Herring Gull (*Larus argentatus*) and a Common Buzzard (*Buteo buteo*).

3.4. Participant context

The intended audience of the programme is upper secondary school students who are taking biology at the mandatory, intermediate, or advanced level. In Denmark, excursions to out-of-school learning environments are less common for upper secondary school students than for primary school students (Danish Agency for Culture, 2009), probably due to a higher work load in upper secondary school. This means that when upper secondary school teachers chose to

bring their students to out-of-school programmes, they do so because these programmes offer something the classroom cannot. Certainly, the upper secondary school teachers we spoke to during the programme indicated that this was the case: They chose to bring their students to the programme because it offered a practical exercise in the subject of evolution, something they themselves found difficult to implement at school. This means that when they came to the museum, the participating students were “primed” to carry out practical work - something that is generally found enjoyable by science learners (Abrahams & Millar, 2008).

To identify authentic instances of palaeontological reasoning and practice among participants in the programme *Evolution: From Dinosaur to Bird*, we observed the interactions between the learners and the objects as these interactions unfolded. We thus observed seven groups of students participating in the programme, each group consisting of 3-5 girls and boys. These observations took place in November and December 2012; for each group we wrote field notes and made video recordings. We had obtained permission to observe and record the participants prior to the visit, and re-confirmed this permission upon their arrival to the museum. For the analysis, we transcribed the discussions of the participants verbatim, adding still frames of the video footage to document the interactions of the participants with the objects (see figure 4A for examples). The discussions and gestures of the participants were then parsed into separate trajectories of inquiry or *participant praxeologies* (an example is given in the following). In this process, we disregarded those activities that were off-task, i.e. unrelated to the objects and the question of *Archaeopteryx*’ flight ability.

In each of the seven groups we observed, the students entered into the didactic contract (Brousseau, 1997/2002) with the Museum Educator; i.e. they accepted the research question given to them and the premise that the answer could be inferred by examining the objects and applying and discussing their existing knowledge. Further, in every case, the students were able to formulate a hypothesis about the flight capability of *Archaeopteryx*, based on their comparisons of the objects. In more than half of the observed instances, students’ trajectories of inquiry were based on the observable evidence and their own knowledge; in fewer instances, students’ trajectories of inquiry were based on their own knowledge, disregarding or misinterpreting the observable evidence. In the following, we describe two trajectories of inquiry carried out by the participants with respect to the furcula and the tail.

Example: The furcula. In the following exchange, a group of programme participants discusses the significance of *Archaeopteryx*’ lack of a furcula (“wishbone”) for its flight capability (please note that because the fossil used in the exercise is a replica of the Berlin specimen, there is no visible furcula).

Anaïs: This one has that wishbone, do you guys remember that? (points to the modern bird skeleton; see figure 4A, left)

Beth: Yes. That one [*Archaeopteryx*] doesn't have a wishbone?

Carla: No... no.

Anaïs: Rather, I can't... it's hard to see (leans in to study *Archaeopteryx*; see figure 4A, right)

Carla: I don't think so.

Beth: So, no wishbone (writes).

(Some minutes go by, and the museum educator asks the group to give an example of their findings)

Beth: The modern bird has a wishbone, and that *Archaeopteryx* doesn't.

Educator: Correct. The wishbone - what is the function of the wishbone in birds?

Anaïs: Doesn't it have something to do with flying?

Educator: What could it have to do with flying?

Anaïs: It's as if it connects, uh, these to the wings. These bones here, connecting them to the rest of the pectoral girdle.

Educator: Yes!

(Some minutes go by, and the participants formulate their hypothesis of *Archaeopteryx*' flight capability)

Beth: To me, there are several things that indicate it couldn't have flown.

Carla: The sternum, and that thing with the wishbone.

Deborah: The wishbone, yes, that makes me think it can't fly.

Anaïs: Yes, it would squash its own chest if it were trying to fly.

In this case, the participants interpret the lack of a furcula on *Archaeopteryx* as a contraindication of its flight capability, citing the strut-like function of the furcula on birds as the main reason. The trajectory of inquiry undertaken by the participants is summed up in the participant praxeology shown in figure 4B.

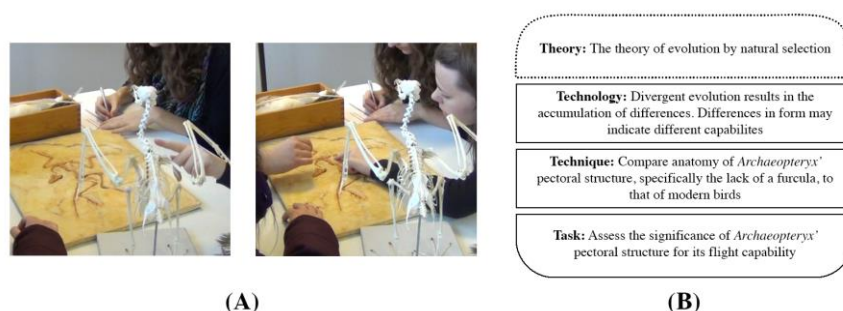


Figure 4. A programme participant observes the presence of a furcula on the modern bird skeleton (A, left) and searches for the (absent) furcula on *Archaeopteryx* (A, right). Their technique and technology are summed up in a participant praxeology (B).

Example: The tail. In the following exchange, a group of programme participants discuss the significance of the bone structure of *Archaeopteryx*' tail for its flight capability.

Ben: That one has a tail (points to *Archaeopteryx*' tail vertebrae; see figure 5A, left.)

Anna: Yes.

Ben: That one does not have a tail. That's not a tail, that thing! (points to pygostyle on the modern bird skeleton).

Anna: There might have been feathers on it.

Ben: But feathers aren't a tail.

Anna: Yes they are.

Arthur: That one has a tailbone (indicates *Archaeopteryx*' tail vertebrae) - a long tailbone.

Ben: Feathers aren't a tail; they're tail *feathers*. A dog has a tail, since it can control its tail (waves arm to simulate movement of dog tail; see figure 5A, right). That one (points to *Archaeopteryx*) can also control its tail; that one (points to the modern bird skeleton) cannot.

The observations of the participants are summed up in the participant praxeology shown in figure 5. The members of the group carry out the technique of comparing the bone structures of the two specimens. Although they interpret *Archaeopteryx*' long bony tail as an appendage that could be controlled, and the tail feathers of a modern bird as something it cannot control, they do not use these observations to generate an explicit technology with respect to *Archaeopteryx*' flight capability (although we could speculate that the group would have predicted that *Archaeopteryx*' tail could have functioned as a rudder in flight, had they considered it); the lack of a technology causes us to categorise this participant praxeology as incomplete.

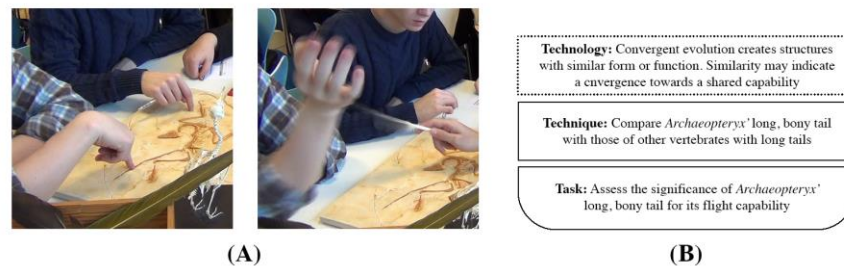


Figure 5. A participant points out the long, bony tail of *Archaeopteryx* (A, left) and compares it to the tail of a dog, waving his arm to show the controlled movement of a dog's tail (A, right). Their technique is summed up in a participant praxeology (B). They do not explicitly discuss the implications of using a dog's tail as a modern analogue of *Archaeopteryx*' tail, but their implied technology (dashed line) is that *Archaeopteryx* was able to fly based on its tail's similarity with those of modern vertebrates (convergent evolution).

4. Analysis

In the following sections, we analyse first the external didactic transposition, then the internal didactic transposition. We summarise by presenting the reference model.

4.1. The external didactic transposition

The external didactic transposition reflects that “what” aspect of the transposition process. In other words, it consists of the decisions that are made regarding *what* parts of the scholarly knowledge are transposed into the officially sanctioned “knowledge to be taught” (Bosch & Gascón, 2006). In the present case, the curriculum guidelines for upper secondary school biology state that the taught subject of biology should take a point of departure in the scientific discipline of biology (Ministry of Education, 2010). Despite biology clearly being considered an *experimental* science in the curriculum guidelines, evolutionary biology (which is largely a *historical* science) is one of the core areas emphasised here.

Although this incongruence seemingly poses a conflict, it is at the same time a “loophole” that allows for the existence of practical programmes based on methods from the historical sciences such as *Evolution: From Dinosaur to Bird*. The ministerial requirement that students should acquire the ability “to explain and apply biological theory and methods, including the analysis and interpretation of data” (Ministry of Education, 2010) can, in the context of evolutionary biology, be interpreted to mean that the scholarly methods of palaeontology, which include analysis and interpretation of data, are purposeful activities for upper secondary school biology students to engage in.

The curricular conflict notwithstanding, the Museum's general education philosophy of using objects and specimens from their collections (or replicas of them) as evidence and sources of information for learners' practical work makes the Museum an obvious source of educational programming to fit the requirements of the curriculum guidelines with respect to evolutionary biology. The “what” afforded by the conditions of the external didactic transposition in the present case is thus a practical, hands-on programme with evolution biology content, involving objects and specimens as data for analysis and interpretation.

4.2. The internal didactic transposition

The internal didactic transposition reflects the “how” aspect of the transposition process. This means that the detailed didactical considerations of *how* particular disciplinary content is to be transformed into a teaching-learning sequence take place in this process (Bosch & Gascón, 2006). The Museum Educator who designed the activity in question is a trained palaeontologist, specialising in bird evolution. He thus has close insights into the particular case of *Archaeopteryx*, and into the various comparative anatomy inquiries that have been carried out

by his colleague palaeontologists. In the following, we focus on the two components of the programme discussed earlier, namely the furcula and the tail.

Example: The furcula. The choice of using just one *Archaeopteryx* fossil replica in the programme, namely the Berlin specimen (see figure 1), was based on considerations of the ability of secondary students to decipher fossil evidence. In particular, the Berlin specimen is almost completely intact and quite well preserved, facilitating its interpretation by untrained observers. The Educator explained how most of the other specimens were fractured into pieces in the course of their particular fossilisation history, and would conceivably be too difficult for programme participants to interpret within the time frame of the programme.

The consequence of this choice is illustrated in figure 4, where participants interpret the absence of a furcula on *Archaeopteryx* as a contraindication of its flight capability. Although this inference is reasonable within the limits of the programme, it is in contradiction to the position held by palaeontologists. Indeed, palaeontologists are aware that fossils differ from each other due to their unique histories and that this affects what can be reliably predicted from them (Ault & Dodick, 2010). Thus, palaeontologists would base their conclusions on careful comparisons of all the known fossil specimens of a species, rather than just one (e.g. Padian & Chiappe, 1998).

One might argue that the use of just one *Archaeopteryx* specimen in the programme is a reasonable choice, given the conditions and constraints inherent in the didactic transposition; however, we suspect an important reflection about the nature of palaeontological inquiry is lost. Specifically, the fact that palaeontology is a historical science, which deals with unique objects with individual histories rather than the “natural kinds” of the experimental sciences (e.g. atoms or chemical compounds; cf. Frodeman, 1995), may be lost upon the participants due to the choice of just one specimen to represent *Archaeopteryx*.

Example: The tail. The choice of using bird skeletons as the organisms with known capabilities to compare to *Archaeopteryx* is no doubt based on the programme’s stated intention of establishing the evolutionary development from dinosaurs to birds (cf. Natural History Museum of Denmark, 2013b). However, the question of whether or not *Archaeopteryx* was capable of flight gave the exercise a more general comparative anatomy form. In this light, we might question the choice of a bird skeleton as the only comparison organism. Indeed, in the programme, participants often spontaneously used other comparison organisms than birds: Figure 5 exemplifies how one group of participants invoked the bone structure of a dog’s tail as a comparison to *Archaeopteryx*. Even though the discussion in this case was inconclusive (that is, the participants did not use their discussion in their hypothesis of *Archaeopteryx*’ flight capability), it is interesting to note how participants spontaneously invoke comparison organisms in addition to the bird skeleton.

This leads us to speculate about the potential benefits of explicitly including other comparison organisms in the programme. Indeed, scholars who work with comparative anatomy often use a variety of organisms with known capabilities as comparisons with the extinct organism they are studying. As mentioned in the preceding, *Archaeopteryx* has been compared a number of other known fliers in various attempts to establish its flight capability. In these comparisons, palaeontologists use both homologies and analogies in their trajectories of inquiry. For example, a comparison between *Archaeopteryx*’ long bony tail and the long tail feathers of certain birds (Norberg, 1995) represents a comparison of analogical features (the tails are superficially similar but have different evolutionary origins) whereas a comparison of the size of the sternum of *Archaeopteryx* and a modern bat (Ostrom, 1979) represents a comparison of homological features (the sternum is a skeletal feature inherited by a common ancestor).

Again, one might argue that there are good reasons for just using one comparison organism in the programme. However, if the objective is to introduce participants to biological theory and methods, including the analysis and interpretation of data (Ministry of Education, 2010), it

seems there may be an opportunity to discuss the notions of analogy and homology as integral components of evolution biology (palaeontology) - an opportunity that is being neglected in the programme.

4.3. The reference model

In the preceding sections, we have presented the analysis of quite specific elements of the programme *Evolution: From Dinosaur to Bird*. A full-scale construction of a reference model would require a more detailed analysis, beyond the scope of this text. Therefore, we present only a few, select elements of the reference model in the following.

The point of departure for the reference model is Brousseau's notion of doing mathematics (here, paraphrased as "doing science"):

The intellectual work of the student must at times be similar to [...] scientific activity. Knowing [science] is not simply learning definitions and theorems in order to recognize when to use and apply them. We know very well that doing [science] properly implies that one is dealing with problems (Brousseau, 1997/2002, p. 22).

In this sense, the milieu provided to the participants through the exercise in *Evolution: From Dinosaur to Bird* allowed for a viable scientific inquiry situation within which a qualified hypothesis of *Archaeopteryx*' flight capability appeared as the optimal solution to the posed problem. The similarity of the participants' trajectories of inquiry to those of real palaeontologists is evidence of the overall scientific authenticity of the situation.

We suggested in the preceding that the programme could conceivably include replicas of several *Archaeopteryx* fossils. Although some of the eleven existing *Archaeopteryx* fossils are quite fractured (see e.g. figure 6) and therefore difficult to decipher, a comparison of a range of different *Archaeopteryx* fossils would make the point that fossils have quite different fossilisation histories that affect what can be predicted from them. This nuance is important, not only because it would align the intellectual work of the participants even more to scholarly palaeontological activity, but because it would help to make the differences between the historical sciences and the experimental sciences clearer. Research shows that the historical sciences are often left out of the portrait of scientific practices, in both national curricula (Gray, 2014) and public discussions (Rudolph, 2007; Wilcove & Eisner, 2000). Certainly, the Danish curriculum guidelines studied in the present text emphasised the experimental nature of biology to the exclusion of its historical aspects (cf. Ministry of Education, 2010). Accordingly, using a range of *Archaeopteryx* fossil replicas in the programme would help establish the point that evolutionary biology or palaeontology uses unique objects as evidence, rather than carrying out controlled experiments on "natural kinds", as the experimental sciences do.



Figure 6. The fossil *Archaeopteryx* (the Thermopolis specimen), photographed at the Wyoming Dinosaur Center.

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<https://www.flickr.com/photos/incidencematrix/14655916050/>. The image has been cropped; no other alterations have been made.

Finally, Brousseau describes how a central component of the teacher's (or in this case, Museum Educator's) role is to produce a situation that allows participants to personalise the knowledge at stake in the teaching sequence. This personalised knowledge should be "a fairly natural response to relatively particular situations" (Brousseau, 1997/2002, p. 23). An example of such a natural response was the spontaneous use by many of the programme participants, of other comparison organisms than the bird skeleton. Participants compared *Archaeopteryx* to modern-day leopards, cats and dogs, as well as other prehistoric animals such as pterosaurs (Achiam, Simony, & Lindow, 2015). Because this practice is seemingly spontaneous among participants, and because it closely resembles the way palaeontologists work, we hypothesise that using a number of comparison organisms in the form of skeletons in the programme would help communicate the various forms of inquiry palaeontology and evolutionary biology might take.

5. Discussion

We have presented evidence of the authenticity (understood as degree of alignment with scientific practice) of the existing palaeontology programme *Evolution: From Dinosaur to Bird*; additionally, we have presented some potentially productive lines of further development of the programme's authenticity. The scope of the present paper has only allowed us to sketch these lines of development; yet, the chosen examples show how perspectives from the theory of didactical situations provide strong and effective scaffolding for this development. We agree with Bosch and Gascón (2006) that TDS constitutes, if not a "machine" to produce reference models, then certainly a powerful framework to connect scholarly knowledge with the evolution of knowledge to be taught, taught knowledge, and learnt knowledge in the development of authentic science education activities.

Going beyond the specific case of *Evolution: From Dinosaur to Bird*, we suggest that TDS may have an important role to play in providing qualified input into broader discussions about authenticity in science education. Authentic science has been described as "a variation of inquiry teaching that aligns closely with how scientists do their work" (Crawford, 2014, p. 113), yet attempts to develop school tasks that reflect real science are in many cases based on simplistic models of scientific activity. Sequential, stepwise, and seemingly universally applicable models of "the scientific method" abound in science textbooks (Woodcock, 2014; Irez, 2016; Pagliarini & Silva, 2007; Cheng & Wong, 2014; Vesterinen, Aksela, & Lavonen,

2013); these models may encourage the belief that science is a simple, algorithmic form of reasoning, reinforcing an unscientific epistemology among learners (Chinn & Malhotra, 2002).

In contrast, TDS takes a fundamentally different approach to the didactic transposition of science. The theory of didactical situations notably focuses on the (often messy) conditions of the particular scientific *situation* that generated an object of knowledge, rather than attempting to apply a generalised and tidy version of scientific inquiry. Indeed, “scientists deploy imagination and imagery, rely upon relevant understandings, and engineer methods of inquiry suitable within particular contexts” (Ault & Dodick, 2010, p. 1101); a science lesson based on TDS by definition incorporates this complexity, resulting in educational situations that more realistically simulate the workings of real science.

Thus, we argue that engaging learners in authentic science situations, that is, situations that require them to mobilise their imagination, to use imagery and relevant understandings, and to engineer suitable methods of inquiry based on the context, can help them construct sound scientific epistemologies. In particular, we suggest that TDS conserves the *internal persuasiveness* of real science. As described by Sharma & Anderson (2009), the didactic transposition of science often reduces this internal persuasiveness, causing science to come across to learners as an authoritative discourse that demands unconditional allegiance. As a counterpoint to this, TDS holds that the “why” of an object of knowledge cannot be learned by reference to the teacher’s authority. It requires a personal conviction that by definition cannot be received from others, but must come from the response of the milieu (Brousseau 1997/2002). In this way, TDS may provide the means to optimise the degree of alignment between real science and authentic science education.

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